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## Design of a hydrogen pulsating heat pipe

Yumeng LIU<sup>a</sup>, Haoren DENG<sup>a</sup>, John Pfortenhauer<sup>b,\*</sup>, Zhihua GAN<sup>a</sup>

<sup>a</sup> Institute of Refrigeration and Cryogenics, Zhejiang University, Zheda Road 38, Hangzhou, 310027, PR China

<sup>b</sup> Department of Mechanical Engineering, University of Wisconsin Madison, 1329 Engineering Research Building, Madison, 53706, USA

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### Abstract

In order to enhance the application of a cryocooler that provides cooling capacity at the cold head location, and effectively spread that cooling over an extended region, one requires an efficient heat transfer method. The pulsating heat pipe affords a highly effective heat transfer component that has been extensively researched at room temperature, but is recently being investigated for cryogenic applications. This paper describes the design. The experimental setup is designed to characterize the thermal performance of the PHP as a function of the applied heat, number of turns, filling ratio, inclination angle, and length of adiabatic section.

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### 1. Introduction

With the development of advanced technology such as superconducting technology and semiconductors, there are some limits for the application of cryocoolers that provide cooling only at the cold head location. For the applications of large-scale superconducting magnets, such as fusion devices and SMES, regenerative cryocoolers in particular are by themselves ineffective at distributing the cooling they produce<sup>[1]</sup>. In order to solve this problem, various groups are presently investigating a novel method which utilizes a highly efficient heat transfer component, the pulsating heat pipe. The pulsating heat pipe has drawn significant amount of attention over the past twenty years

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\* Corresponding author. Tel.: +1-608-263-4082; fax: +1-608-262-8464.

E-mail address: [pfot@engr.wisc.edu](mailto:pfot@engr.wisc.edu)

**Nomenclature**

D	inner diameter	WF	working fluid
N	turn numbers	FR	filling ratio
$\beta$	inclination angle	$\rho_l$	working fluid density of the liquid phase
$\rho_v$	working fluid density of the vapour phase	m	mass
g	the acceleration of gravity	T	temperature
$q_{in}$	the input heat	$q_{out}$	the heat leaving
$c_p$	heat capacity		

The pulsating heat pipe (PHP) was first proposed by Akachi in the early 1990s<sup>[2]</sup>. It has a long capillary pipe bent into many turns, and is composed of a condenser section, adiabatic section and evaporator section. Due to the effect of capillary forces, the vapor slugs and liquid plugs forming in the capillary pipe after it is partially filled with the working fluid will transfer heat from the evaporator to the condenser section through self-oscillation and phase change. PHPs are similar to conventional heat pipes, with regard to their high conductivity and variable heat flux. However, they provide additional advantages such as a simple structure, low processing cost and insensitivity to gravity, benefits that have created a large amount of interest in their development.

The pulsating heat pipe affords a highly effective heat transfer component that has been extensively researched at room temperature, but is recently also being investigated for use in low temperature applications, which will be introduced carefully in the next section.

## 2. The research of cryogenic pulsating heat pipe

Cryogenic pulsating heat pipes typically utilize the cooling capacity from cryocoolers, rather than the usual liquid-circulation cooled condenser associated with room temperature applications. The cryogenic pulsating heat pipe therefore serves the crucial function of spreading cooling from the localized region of a cryocooler cold-head to the larger regions associated with cryogenic applications, such as a superconducting magnet.

The research to date on cryogenic pulsating heat pipes is summarized in table1. In the table1,  $\beta=90^\circ$  means that the condenser section is above the evaporator section;  $\beta=0^\circ$  means condenser section and the evaporator section are in the horizontal direction;  $\beta=-90^\circ$  means evaporator section is above the condenser section. UM means University of Missouri; NIFS means National Institute for Fusion Science of Japan, UW-Madison means University of Wisconsin Madison.

Table1. The research summary of cryogenic pulsating heat pipe<sup>[3]-[9]</sup>

Institute	WF	Capillary pipe		N	FR (%)	Heat (W)	$\beta(^\circ)$	Thermal conductivity (W/m · K)
		Material	D(mm)					
UM	N2	Cu	1.65	8	48	20.5~380.1	0	11600~26100
CEA-France	He	Cu-Ni	0.5	5	-	0.015~0.145	0~40	18700
NIFS	H2	SSL	0.78	5	31~80	0~1.2	90	500~3000
			1.58	5	50~72.2	0.588~16	-90~90	2220~11480 (0-90°)
			0.78	5	17~70	0~7	90	5000~18000
			0.78	5	16~95	0~1.5	90	1000~8000
			1.58	5	50.6~86.1	0.588~16	-90~90	5100~19440 (0-90°)
UW-Madison	He	SSL	0.5	32	4~26.5	0.003~0.086	0	1800~2457

The research at the University of Missouri has focused on the large cooling capacity from a liquid nitrogen pulsating heat pipe running successfully and efficiently in the horizontal direction with a small number of turns; the group at CEA-France built a helium pulsating heat pipe, and focused on the pre-cooling system and the influence of the inclination angle; the group at the National Institute for Fusion Science of Japan studied the influence of working fluid, filling ratio, input heat and inclination angle on the performance of cryogenic pulsating heat pipes. They also investigated cryogenic pulsating heat pipes with a small number of turns and a small applied heat, and found that the PHP cannot operate when the inclination is less than or equal to zero; The University of Wisconsin Madison built a helium pulsating heat pipe with 32 turn numbers that operates efficiently at zero inclination. However, up to now, there is no relevant research about cryogenic pulsating heat pipes in China.

Because the research about cryogenic pulsating heat pipes is just beginning, there are many issues to address both through experimental and theoretical research. By comparing with pulsating heat pipe development at room temperature and by studying the specific details of cryogenic pulsating heat pipes, this paper proposes various research interests on cryogenic pulsating heat pipes as follows:

- Visualization. The capillary pipe of cryogenic pulsating heat pipes is usually copper or stainless steel instead of glass. Visualization methods would enable better understanding of the oscillating behavior and the distribution of the vapor slug and liquid plug.
- Influence of gravity. Cryogenic pulsating heat pipes will be of great value especially in the aerospace field if they can operate independent of the angle of inclination.
- Efficient connection method between capillary pipe and cold head: According to the cryogenic pulsating heat pipe research of the Japanese group, the main temperature difference is produced at the connection of the PHP with the condenser and evaporator sections.
- Modeling. The theoretical research of pulsating heat pipes involves two phase flow and complex oscillation mechanisms which make the theoretical research challenging. Previously published analyses have provided some heat transfer models and semi-empirical correlations for pulsating heat pipes. However, as of yet, there are no theoretical reports directly addressing cryogenic pulsating heat pipes.

In order to address problems (2) ~ (4), this paper proposes a hydrogen pulsating heat pipe. The details of the experimental setup are introduced as follows.

### 3. The design of a hydrogen pulsating heat pipe

The first step to design a pulsating heat pipe experimental setup is to determine the working temperature, which requires one to define the working fluid. The temperature range of liquid hydrogen or liquid neon is especially significant for superconducting applications. In that hydrogen offers the possibility of cooling either low temperature superconductors, such as  $\text{Nb}_3\text{Sn}$  or high temperature superconductors ( $\text{MgB}_2$ ), we have elected to investigate the properties of a hydrogen based PHP.

In addition to the working fluid, the other difference between the cryogenic pulsating heat pipe and pulsating heat pipes operating at the room temperature is the cold source. The hydrogen pulsating heat pipe in this study obtains its cooling from a GM cryocooler. As with all cryogenic applications, provision for minimal heat leaks, instrumentation, and thermal contraction make the experimental arrangement more complex than room temperature systems. The details of the hydrogen pulsating heat pipe experimental setup are introduced as follows.

#### 3.1. Introduction of experimental setup

The hydrogen pulsating heat pipe being prepared in this case provides many variable parameters, such as the number of turns, the length of the adiabatic section, the inclination angle, the filling ratio and the heat input, all of which will have an influence on the heat transfer performance of the pulsating heat pipe. The experimental setup includes a dewar, shield, cryocooler, pulsating heat pipe element, heater, thermometer, and data collection system as shown in Fig. 1.

An appropriate size for the capillary pipe is required in order to form the alternating distribution of vapour slugs

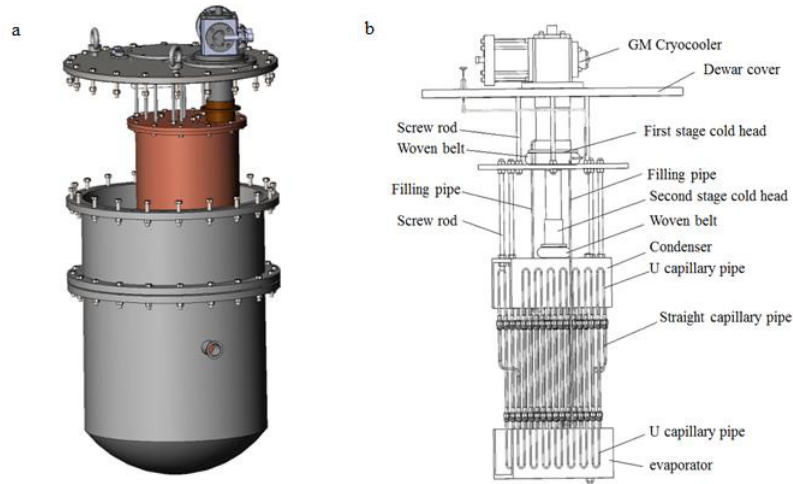


Fig. 1 (a) 3D structure of experimental setup; (b) Plane structure of experimental setup.

and liquid plugs, which is the basic prerequisite for the oscillation movement. According to the research of White and Beardmore, capillary forces will dominate over the force of gravity, and produce the alternating distribution of vapor slugs and liquid plugs when  $Bo < 2$ :

$$Bo = \sqrt{\frac{g(\rho_l - \rho_v)}{\sigma}} D. \quad (1)$$

Using equation (1), the selected value for the inner diameter of the capillary pipe is 2.3 mm, and the temperature is 27 K at that capillary pipe size. Above this temperature, the force of gravity becomes comparable and larger than the capillary forces, and the performance of the PHP is expected to change significantly.

The pulsating heat pipe element, comprising the major structure of the experimental setup, is shown in Fig. 1 and is composed of the condenser section, adiabatic section and evaporator section.

The condenser section is similar with the evaporator section, and made up of a U-shaped copper block with 4 parallel surfaces, two on the inside and two on the outside. A total of 28 grooves machined into the surface provide locations for the ends of the capillary pipes which are also copper, to be brazed onto the copper block, as shown in Fig. 2. Because of the high conductivity of copper, the temperature of the working fluid can be approximately regarded as the wall temperature of the copper capillary pipe. Swagelock VCR connectors are used to connect the U-shaped sections of the capillary pipe with the straight sections of the capillary pipe. Therefore, the number of turns comprising the closed loop pulsating heat pipe element can be changed in the range of 1 to 28 and the length of the adiabatic section can be modified by changing the length of the straight capillary pipes.

The dewar, made up of 3 separate axial sections, with an inner diameter of 560 mm and an overall height of 1300 mm, provides a vacuum down to the value of  $5 \times 10^{-5}$  Pa. In order to change the inclination of the setup, a rotating bracket is included at the mid-height of the dewar allowing the whole dewar to be rotated about this pivot point.

In order to reduce the thermal radiation heat load on the PHP, a copper shield is included inside the dewar, and supported at the dewar cover through small diameter stainless steel rods. The thermal shield is thermally connected to the first stage of the cryocooler. The dimensions of the shield are as follows: the inner diameter is 316 mm, the thickness is 2 mm and the height is 960 mm. The pulsating heat pipe element is enclosed by the shield, and also suspended from the shield cover by a number of stainless support rods.

The cryocooler adopted for the present experiment is model KDE410 provided by the Nanjing cooltech cryogenic technology co., ltd, and supplies 1W of cooling power at 4.2 K. The first stage of the cold head is connected with the shield cover, while the second stage is connected directly with the pulsating heat pipe element. To avoid exerting

force upon the cryocooler and causing a bad effect on its performance, a flexible connection is included between the cryocooler and the PHP condenser.

### 3.2. Structure calculation

As shown in Fig. 1, the entire pulsating heat pipe and the copper shield are suspended via support rods. The mass of the shield is 32 kg and the mass of the pulsating heat pipe element is 20 kg. Therefore, the suspension of pulsating heat pipe depends on four 10 mm diameter stainless steel rods with a length of 280 mm support the pulsating heat pipe from the shield cover, while seven 12 mm diameter stainless steel rods with a length of 200 mm are used to support the copper shield from the dewar cover.

Because the experimental setup needs to change its inclination angle, all the rods must be strong enough to bear the bending stress. Based on the mass and configuration of the pulsating heat pipe, the average tensile stress on its support rods is 0.64 MPa, the average bending normal stress is 142.6 MPa and average bending shear stress is 0.85 MPa; The same considerations for the shield support rods reveal an average tensile stress of 0.66 MPa, an average bending normal stress of 87.6 MPa and an average bending shear stress of 0.88 MPa. The corresponding limiting values for stainless steel are a yield stress of  $[\sigma]=630$  MPa, and a shear stress  $[\tau] = 77.5$  MPa. If the safety factor is 3, and then  $\sigma_{\max}=210$  MPa;  $[\sigma]_{0.2}=215$  MPa, in the situation of safety factor being 1.5, then  $\sigma_{\max}=143$  MPa, the design meets the requirement.

### 3.3. Heat leak calculation

As with all cryogenic experiments, the heat leak calculation is very significant, since among other issues, it has a direct effect on the available cooling capacity of the cryocooler. The following sections address the steady state heat load at each of the two stages of the cryocooler.

#### 3.3.1 Heat load and cooling capacity at the first stage cold head

The heat load on the first stage is mainly due to that absorbed by the shield, either through the support rods, the gas supply pipe for the PHP or via thermal radiation.

Shield. The temperature of the shield is simulated utilizing ANSYS software. The assumptions included in the simulation are as follows:

- The initial ambient temperature is 300K;
- The balance of heat load and cooling capacity determines the cold head temperature of the first stage. The resulting first stage temperature and heat load are 36 K, and 15 W respectively;
- The copper shield is surrounded by a 26 layer MLI blanket, and the emissivity of the shield is 0.02.

The simulation results reveal that the temperature difference between the top and the bottom of the shield is about 2 K. Therefore, shield can provide a 36 K working environment for the cryogenic pulsating heat pipe.

From the steady state heat load calculations, we find that the radiation heat load contributes about 1.5 watt, while the conduction heat load through the stainless steel support rods and filling pipe contribute 12 watt and 0.5 watt respectively.

#### 3.3.2 Heat load and cooling capacity at the second stage cold head

As described above, the total heat load to the first stage cold head is about 15 W. A set of measurements were made to determine the cooling performance of the cryocooler, and the results are shown in Fig. 3. As shown, with a heat load of 15 watt on the first stage and a corresponding operating temperature of 36 K, the second stage can provide in excess of 14 W of cooling for temperatures higher than 20 K.

The components contributing to the heat load on the second stage include conduction through the support rods extending from the shield to the condenser, radiation from the shield to the php, and conduction through the filling pipe. The conduction heat leak through stainless steel rod is the major part, and that is only about 55 mW. Thus, the available heat load that can be transferred through the PHP is nearly 13 watt.

### 3.4. Cool down calculation

In order to estimate the time required to cool the experiment from room temperature to its steady state condition, a numerical model was developed that coupled time dependent energy balance equations for the thermal shield, condenser, and evaporator. Each of these three objects was treated as lumped capacitance solids, and the time dependent energy balance relations are:  $\sum_i (mcp)_i \frac{dT}{dt} = \sum (q_{in} - q_{out})$ .

Note that the temperature dependence of  $c_p$  as well as each of the heat transfer ( $q$ ) terms is explicitly included in the model. The results of the model reveal that it will require less than one day for the experiment to cool down.

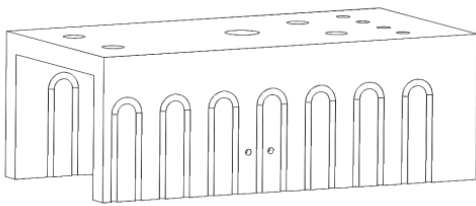


Fig. 2. The condenser section of pulsating heat pipe.

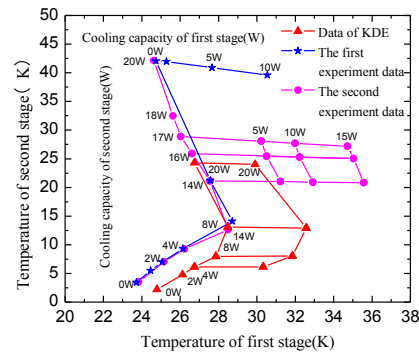


Fig. 3. The curve of cryocooler performance.

## 4. Conclusion

This paper summarizes the previous research regarding cryogenic pulsating heat pipes, and provides design details of cryogenic pulsating heat pipe being fabricated at Zhejiang University. The experimental setup will be able to study the effect of many parameters on the heat transfer performance of the pulsating heat pipe, such as the number of turns, the filling ratio, inclination angle, the length of adiabatic section and the applied heat, all of which are of great significance for the application of cryogenic pulsating heat pipes.

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